D-4667

Reactiveness and Fragmentation
in
Maintenance Management

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November 1996 WP#3935

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Abstract

Fragmentation and reactiveness have been identified as two barriers to organizational learning. This paper examines the impact of these two factors on the performance of a maintenance system by developing a system dynamics model. The paper shows that reactive policies without a system perspective appear to be self-approving in the short run and cause the reoccurrence of some maintenance crises in the long run. The reoccurrence of maintenance problems created by reactive policies disappear when a proactive policy designed within a system perspective is simulated.

1. INTRODUCTION

The rate at which organizations learn has come to be considered a major sustainable competitive advantage (Stata, 1989; Senge, 1990). Interest in how organizations learn and ways to improve their learning process has grown (Argyris C. and Schon D., 1978; Senge, 1990; Huber, 1991; Nevis, DiBlla, and Gould 1995). Linkages between individual learning processes, which have been more deeply investigated in the past, and organizational learning, as a more recent endeavor, have been analyzed (Kim, 1993) to create a better understanding of the ways that organizations learn through and from the learning of their individual members. As organizational learning has been recognized as an important competitive advantage, understanding the barriers to learning has become more important, too. Hence, barriers and breakdowns in individual learning (Sterman, 1994; Kim, 1993) and organizational learning (Kim and Senge, 1994; Kofman and Senge, 1993) have been discussed. Kofman and Senge (1993) present some "*areas of cultural dyisfunction*" that are pervasive, tacit, and deeply rooted assumptions and ways of thinking that impede effective learning. Two of those dyisfunctions are fragmentation and reactiveness, which will be discussed in this paper within the context of maintenance management.

Kofman and Senge (1993) argue that fragmentation obscures the relationship, the connectedness, and the characteristics of the whole. They maintain that "*Rather than thinking of a world of 'parts' that form 'wholes', we start by recognizing that we live in a world of wholes within wholes." (p. 13.)* They advocate system views and systems thinking as a required discipline for deep learning as it has been emphasized by others (Forrester, 1961; Sterman 1994; Senge, 1990). They generally argue that since systems and–feedback structures are ubiquitous -- that we are surrounded and are part of interrelationships that create our world -- systems thinking and the correct perception of feedback structures are required for effective and deep learning. Lack of systems thinking and "misperception of feedback," especially in situations with a high degree of dynamic complexity, and where cause and effect are not closely related in time and space, make learning very difficult. Sterman and his colleagues have generated substantial experimental evidence and shown that dynamic complexity -and "misperception of feedback" slow down learning even when time and space are compressed in a virtual world of flight simulators (Sterman 1989a,b; Paich and Sterman, 1993, Diehl and Sterman, 1995).

Reactiveness, another cultural impedance to learning, is change in reaction to outside conditions. Kofman and Senge (1993) argue that while the wellspring of real learning is aspiration, imagination, and experimentation, we have grown up emphasizing reaction to outside forces as the engine of change and learning. They say "*the persuasiveness of a reactive stance in management is evident in the fixation on problem solving....The problem solver tries to make something go away.* " When a reactive mode

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of decision making is combined with fragmentation and lack of systems thinking, reactive decisions and actions will often neither result in effective learning nor solve the problem. To learn effectively and create desired changes, as discussed by systems thinkers such as Forrester (1961) and Senge (1990), requires practice and use of systems thinking disciplines.

In this paper, a reoccurring maintenance problem is discussed to show how fragmented and reactive views have failed to create learning and deliver a desired result. The next section presents a maintenance problem and managerial decision rules based on a fragmented and reactive mode of management. Then in Section 3, the problem is put into a system perspective. Within systemic thinking both reactive and proactive modes of management can be formulated and examined. Section 4 examines the behavior of the system under a reactive mode and shows how reactive management can lead to a reoccurring problem without much learning over time. In Section 5, based on understanding provided through a system perspective, a proactive policy is designed to improve the performance of the maintenance system. Systems thinking, system modeling, computer simulation, and a proactive perspective in policy design could help effective learning and performance improvement.

2. PROBLEM STATEMENT

2.1 Discontinuity in Preventive Maintenance Plans

Maintenance programs are divided into reactive and proactive programs. In reactive maintenance, repairs are made when equipment fails. Proactive maintenance (PM) is a form of preventive or predictive maintenance. Preventive maintenance is the regularly scheduled process of performing certain types of maintenance, inspections, adjustments, and lubrications on equipment prior to failure. The objectives of preventive maintenance programs include reducing the incidence of breakdown or failure of equipment, extending the useful life of production machinery, and improving product quality (Bateman, Jon F, 1995). In predictive maintenance, the condition of equipment is observed, and at the right time before it breaks unexpectedly, required maintenance is done (Stevens Tim, 1995).

While it is being recognized that "the higher production uptime and product yields more than justify the -expense of their preventive-maintenance programs"(Schriefer John, 1995, Thielsch, Helmut; Cone, Florence, 1995), many plants experience frequent wanes in their proactive maintenance programs. Proactive maintenance programs weaken for different reasons. When the backlog of broken equipment rises, preventive and predictive maintenance work are considered to have lower priority and are delayed (Brown, Michael V). Under cost cutting pressure, in order to reduce maintenance cost, all of the cut has to come from activities such as planning and preventive maintenance (Swanekamp, Robert, 1995) rather than corrective maintenance, because broken equipment must be fixed. As a result "a culture of reactive maintenance" is developed. For example, in research on maintenance management in Du Pont, it has been concluded that ".. *it is difficult to establish and maintain preventive maintenance practices in the face of continuing pressure for immediate production and cost-cutting efficiencies*" (Carrol, et al. 1993, p. 30). Some plants have shown oscillatory behavior back and forth between preventive and reactive maintenance without much learning about the causes. For example, as one of the managers of a refinery in Ohio explains:

> "A plant example of oscillation is our approach to preventive maintenance. In 1985 Lima Refinery had a pretty effective PM program. This worked to

identify all upcoming failures early enough to plan repairs, shutdown before a failure event, etc. It worked. But this success had the side effect of lowering the amount of failures to the point where the inspectors weren't finding anything much to repair (this was good), such that management perceived them to "not be busy enough." The people responsible for lowering the failures (both salaried and hourly) were given other duties "to fill their idle time" such that they got away from the work of preventive maintenance and onto more immediate reactive repairs. This caused failures to increase again, and oscillation happened. Some anecdotal comments are that long term employees have seen PM programs come and go 4 or 5 times in their career. They wonder why we didn't stick with such a good thing." (Manus P., 1995, p.9)

Such oscillation in the maintenance system is not desirable. Oscillation causes the plant to lose its trained maintenance staff, to bear a higher cost for maintenance under crisis condition in a reactive mode. It also causes personnel problems and instability in the management.

Lack of continuity in successful implementation of proactive maintenance is costly. The interruption of production process when equipment breaks decreases productivity and increases cost. Sudden shut-down and startup processes stress the plant and equipment; decrease the life of equipment; require operators and mechanics to work overtime under pressure; and could prevent the plant from delivering product to customers on time thereby damage the market share of the company. While the advantages of proactive maintenance have been established, many plants move back to reactive maintenance after some successful but short--lived efforts to implement proactive maintenance. Reactiveness and fragmentation in some major managerial decisions are the forces behind such backward movement.

2.2 Reactiveness and Fragmentation in Maintenance Decision Making

There are two major and interrelated managerial decisions in maintenance management. One decision is concerned with allocation of resources to maintenance. The other decision is about the percentage of equipment that should be covered by proactive maintenance as a goal. Below, each decision is examined when it is made under reactiveness and fragmentation condition.

A) Resource allocation:

For the sake of simplicity, this paper considers maintenance staff the only resource that is allocated to maintenance. Staff could represent other resources, such as space or working capital, or alternatively we can assume that other resources are always available at desired levels. Under fragmentation and reactiveness, as shown in Figure 1, a desired number of staff is set in reaction to two kinds of pressure: pressure from broken equipment and pressure from cost reduction.

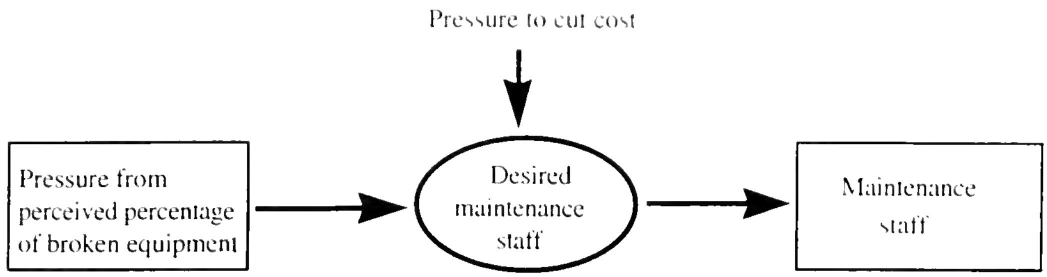


Figure 1: Desired maintenance staff as influenced by two pressures in a reactive decision making.

When pressures to cut costs rise, management reacts by decreasing maintenance staff. Pressures to cut costs could arise for different reasons, such as severe competition or financial shortages, or the desire to make higher profit in the short run. In fragmentation or non-systemic decision making, the impact of the reduction of maintenance staff on any other part of the system is not considered. Only one fragmented causal relationship between maintenance staff and maintenance cost is considered: lower maintenance staff would lead to lower maintenance costs at least in the short run. Reactiveness implies that when the percentage of broken equipment increases and plant uptime falls and products can not be delivered on time, management will react by making a decision to increase maintenance staff. But when the perceived percentage of broken equipment is low, then in a reactive mode, management yields to the pressure from cost reduction and desired maintenance staff drops. As was found in Du Pont, (Carroll et. el. 1993 p.27), "Yet the mental models of managers are strongly conditioned by cost-cutting pressure to pare back resources when there no longer appears to be a need. A team member [from Du Pont] worried that "As soon as you get the problems [of broken equipment] down people will be taken away from the effort and the problems will go back up."" But, without a system perspective, the impact of staff reduction on other parts on the system will not be considered. Pressures to cut costs might vary as severity of competition or financial conditions changes, but in order to keep the model simple, cost pressures are assumed to be constant but present. Under this assumption, the management decision to increase or decrease maintenance staff would be in reaction to the perceived percentage of broken equipment.

B) Preventive Maintenance Coverage Ratio

Another managerial decision in the area of maintenance is to set a goal for the percentage of equipment under preventive maintenance. In a reactive mode, when broken equipment increases and uptime falls and products are not delivered to the customers according to sales contracts, maintenance improvement becomes a hot issue. Expansion of preventive maintenance becomes the agenda of the day. The desired percentage of equipment under proactive maintenance, as a management goal, increases. Figure 2 shows a reactive causal relationship in which as perceived broken equipment increases, so does the desired percentage of equipment under proactive maintenance. In addition to broken equipment, in a reactive mode, the availability of maintenance staff is another determinant of desired percentage of equipment under proactive maintenance. As has been found in the case of Du Pont, "When maintenance departments are asked to cut expenses, nearly all the cut has to come from activities such as planning and preventive maintenance rather than corrective maintenance, because breakdowns in critical equipment must be fixed."

Again, a fragmented perspective does not consider the interaction between this decision and other decisions and variables in the plant. The next section puts these two reactive decisions within a system perspective.

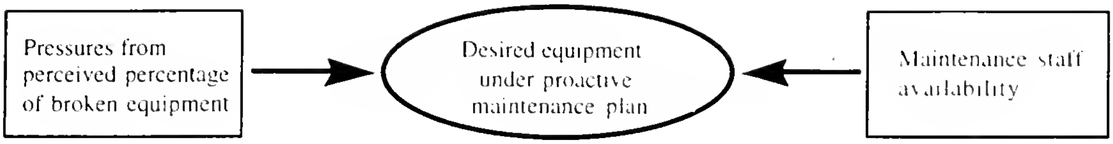


Figure 2: Desired proactive maintenance coverage is set in reaction to broken equipment and staff availability.

3. A SYSTEM PERSPECTIVE

Systems thinking, or "primacy of the whole" as Kofman and Senge (1993) call it, considers each decision as an element in a network of interacting elements which form a system related to the issues of concern. Using System Dynamics methodology (Forrester, 1961; Richardson and Pugh III, 1981; Richmond et al., 1987), this section puts the above reactive and fragmented decisions into a system perspective.

3.1 Stock and Flow

In System Dynamics, stocks and flows are the two basic variables in a system. Stocks and flows represent flows and accumulations that take place in the system and are relevant to the problem or issues under study (Forrester, 1961, Richmond et al. 1987). Flows to the stock are regulated by feedback loops between stocks and flows. Addition of the feedback loops to the stock and flow structure will complete the system perspective.

Figure 3 shows the stocks and flows structure of a maintenance system_model that are relevant and sufficient for the purpose of this paper. Stock variables are shown as rectangles, and flows are shown as circles with a valve sign on top. There are five stocks or level variables. One level variable is for *maintenance staff* which can be increased and decreased by a flow called *change in maintenance staff*. This rate represents either hiring and firing rate or rate of transfer between maintenance department and other parts of the plant.

The other four levels represent the existing equipment in the plant. The equipment is either operational or under repair. There are two groups of operational equipment. One group is under proactive maintenance and is called *Equipment Under Proactive Maintenance Plan* [1]. The other operating group is called *Equipment Under Reactive Maintenance*. Equipment that is not operational is under repair. Some equipment is withdrawn from operation for preventive maintenance. This group is represented by a level called *Equipment Under Proactive Maintenance Repair*. The remaining equipment is broken and is under regular or reactive maintenance and is called *Equipment Under Reactive Repair*

Equipment flows between stocks. Different flows between stocks can be grouped into the following categories:

A. Breakdown rates

There are two break-down rates:

- *Break-down of equipment under reactive maintenance* that presents the breaking rate of equipment which is under reactive maintenance.

[1] In this model preventive maintenance represents all proactive modes of maintenance. This includes preventive as well as predictive maintenance. In both, equipment is examined and repaired before breakdown

- *Break–down of equipment under proactive maintenance.* presents the breaking rate of equipment which is under proactive maintenance. Although the chance of equipment breakdown under proactive maintenance is low, still that equipment might break and move to the stock of equipment which is under reactive repair.

B. Transfer of equipment to do proactive maintenance

There is one flow in this group, as shown in Figure 3:

- *Equipment transfer to proactive maintenance* represents a rate at which equipment that is under proactive maintenance is taken out of operation for proactive maintenance before it breaks.

C. Transfer of operating equipment between proactive and reactive plans

There is one rate in this group too:

- *Transfer of equipment to proactive plan* represents the transfer of equipment to proactive maintenance from reactive maintenance. A negative value for this rate represents transfer from reactive to proactive plan. The size and direction of this flow is regulated by management.

D. Equipment repair rates

There are three flows from equipment under repair to operational equipment:

- *Proactive maintenance completed* represents the rate at which proactive maintenance is completed and equipment under proactive maintenance is returned to operation
- *Repair of equipment ∗ under proactive maintenance* represents the rate of reactive maintenance of that broken equipment which was under proactive maintenance but broke down. This rate returns the broken equipment to operation under proactive maintenance plan.
- *Repair of equipment ∗ under reactive maintenance* represents the rate of reactive maintenance of those broken equipment that were under reactive maintenance but broke down. This rate returns equipment to operation under reactive maintenance plan.

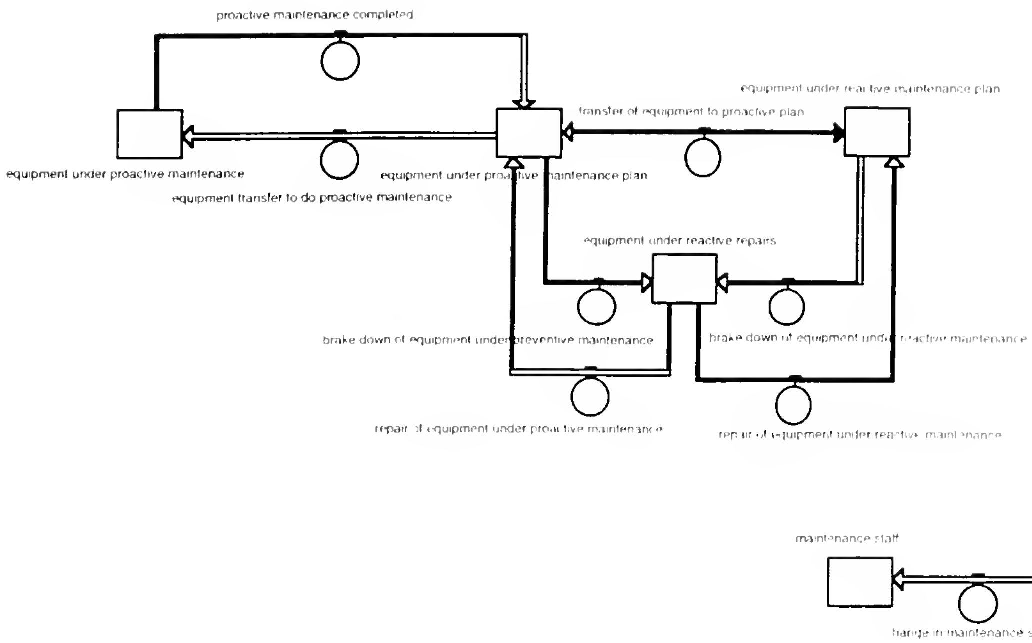


Figure 3: Stocks and flows structure of the model.

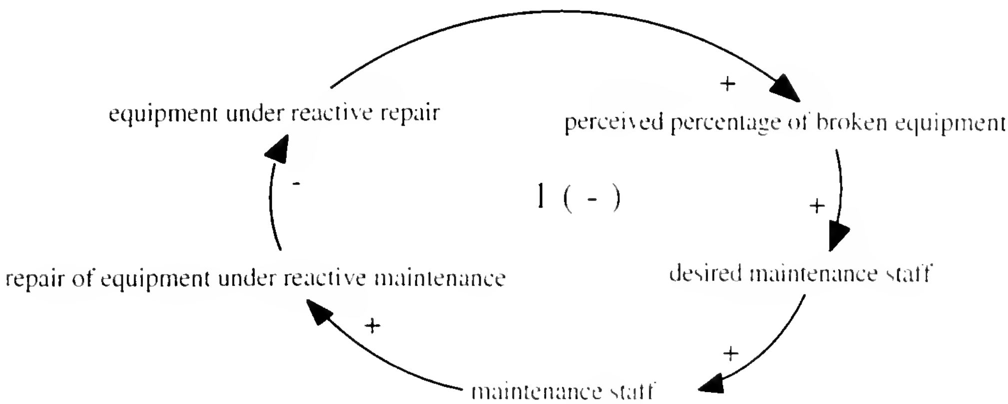
In this model depreciation is ignored and it is assumed that whatever is depreciated, is replaced, and the net rate of depreciation is *zero*. Of course when equipment is depreciated and replaced with new equipment, the breakdown rate of the new equipment might be less. But since the purpose of this paper is to develop a simple model that can explain the oscillatory behavior of the maintenance programs under reactive policies, the assumption of zero net depreciation flow will not be of considerable importance.

There are two more stocks in the model, shown in Figure 4, that are used to calculate some performance indexes. One stock is *accumulated staff time* which represents the total time of maintenance staff during the simulation as measured by man-year. *Accumulated staff time* is initialized at zero and accumulates the available staff time during the simulation. The value of *accumulated staff time* at the end of simulation shows the amount of resources in terms of staff time that have been used during the simulation for the maintenance. The other stock is *accumulation of non-operating equipment* to determine the total non-operating equipment during the simulation in terms of equipment-year. *Accumulation of non-operating equipment* is initialized at zero and accumulates over the simulation with the rate of *non-operating equipment. Non-operating equipment* is simply the difference between total equipment and operating equipment, which is-operating either under a preventive maintenance plan or reactive maintenance.

Figure 4: Stocks and flows to calculate performance indexes.

3.2 Major Feedback Loops

Stocks and flows are connected and regulated by feedback loops (Forrester 1961, Richardson and Pugh, 1981). Although there are many loops connecting stocks and flows in the model, this section only presents the major feed-back loops which include reactive and fragmented decisions presented in Section 2. Presentation of reactive decisions in a feedback loops framework puts them into a system perspective. Figure 3 shows the effect of reactive decision making on staff within a major negative feedback loop of third order, with three integrations taking place within it, which can generate oscillation[2].



Reactive decision rule to change maintenance staff based on perceived broken equipment shapes a major negative loop that creates oscillation.

Figure 5: Major negative feedback loop that generate oscillation.

In Figure 5, some of the intervening variables are not shown to reveal the essence of the loop more clearly. As shown in the figure, when *Equipment Under Reactive Repair* increases, so does the *Perceived Percentage of Broken Equipment* because more equipment under repair means more equipment is broken and the percentage of broken equipment is higher. Higher percentage of broken equipment would be finally perceived by the management and therefore result in a higher *perceived percentage of broken equipment*. As *perceived percentage of broken equipment* increases, management would react by increasing the number of *Maintenance Staff* to repair high accumulation of broken equipment and bring them back to operation. As *maintenance staff* increases, they can repair more equipment and the rate of *repair of equipment under reactive maintenance* would increase. As the rate of repair increases, *equipment under reactive repair* would decrease more rapidly and the loop is closed. As the behavior of the model will show, loop 1 by itself can produce oscillation as a result of reactive decision rules to change maintenance staff. However, there are some more essential loops that can accentuate the oscillation.

Figure 6 shows two more negative feedback loops that operate in a reactive mode of decision making. Both loops are negative and are of the order of higher than two and can accentuate the potential oscillatory behavior of loop 1. Both loops represent reactive decisions to change the equipment under a preventive maintenance plan. In loop 3, as *maintenance staff* rises and more resources become available to do preventive maintenance

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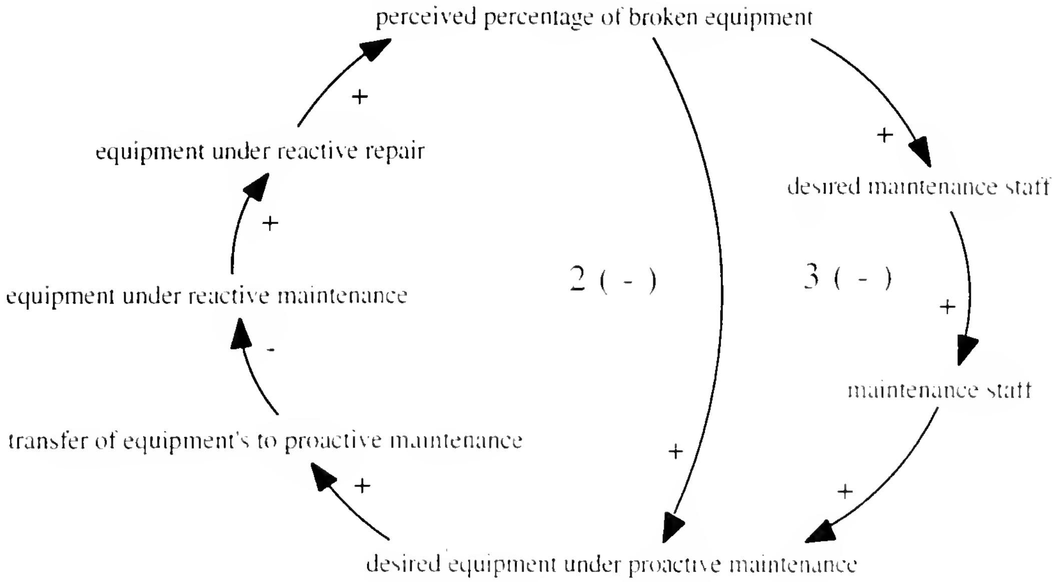
[2] The three integrations in feedback loop 1 are in *maintenance staff*, *equipment under reactive repairs*, and *perceived percentage of broken equipment*. *Perceived Percentage of Broken Equipment* is to model an information and perception delay. Level variables that represent information delays were not presented in the previous section.

in addition to the reactive repairs, *transfer of equipment to proactive maintenance increases* and more equipment is transferred to proactive maintenance plan. At a more detailed level of model equations, presented in the appendix, *Maintenance Staff* is compared with the required staff to do different kinds of repairs, then if *Maintenance Staff* is more than required staff, availability of staff will be considered high and desired equipment under proactive maintenance increases. If availability of staff is low, then because repair of broken equipment usually has a higher priority, proactive maintenance is postponed and *equipment under preventive maintenance plan* drops.



Reactive decision to transfer equipment to proactive maintenance based on availability of maintenance staff and the percentage of broken equipment accentuate oscillatory behavior of the reactive mode.

Figure 6: Two other major negative feedback loops strengthening oscillatory behavior._

An increase in *perceived percentage of equipment broken* invokes another reaction in addition to increase in staff. A high percentage of broken equipment indicates a poor maintenance management and is a sign of operational crisis because of too much_broken equipment. Under such conditions, management reacts to improve maintenance management by expanding preventive maintenance programs and increasing *desired equipment under preventive maintenance plan*, as shown in Figure 6. As *desired equipment under preventive maintenance plan* increases and this reactive managerial decision gets implemented, *transfer of equipment to proactive maintenance* rises and decreases *equipment under reactive maintenance plan*. Lower *equipment under reactive repair* would result in lower broken equipment and finally lower *perceived percentage of broken equipment* and vice versa. The last causal link closes both loops 2 and 3.

3.3 Reactive decision rules

A complete list of model equations is presented in the appendix. However, in this section the equations for two reactive policies, governing change in staff and transfer of equipment to proactive maintenance plan, are discussed.

As explained previously, desired maintenance staff is set in reaction to the percentage of broken equipment, and maintenance staff is adjusted toward the desired value over time. Suppose that:

s = maintenance staff
d = desired maintenance staff
b = perceived percentage of broken equipment to a normal percentage
T = time to adjust maintenance staff
m(b) = multiplier from broken equipment for desired maintenance staff and an increasing function of b.

Then the equation for the reactive policy to change staff in reaction to broken equipment is:

$$\frac{ds}{dt} = (d - s) / T \qquad (1)$$

$$d = m(b) \cdot s \qquad (2)$$

where ds/dt is derivative of s over time and $dm(b)/db$.

In equation 1, s is adjusted towards the desired value of maintenance staff d. In equation 2, to determine *desired maintenance staff, d, maintenance staff* is modified by a multiplier from broken equipment, $m(b)$. $m(b)$ is an increasing function of b, such that when *perceived percentage of broken equipment, b,* increases so does m. When b is less than one, indicating that broken equipment is less than normal, then m will be less than one to set *desired maintenance staff, d,* at a value less than current *maintenance staff, s.* And when b is more than one, indicating that broken equipment is more than normal, then m will be more than one to set *desired maintenance staff, d,* at a value more than current *maintenance staff, s,* in order to increase staff in reaction to high percentage of broken equipment.

Under reactive policies, the transfer of equipment to proactive maintenance plan is set in reaction to changes in broken equipment and maintenance staff availability. Suppose that:

e_p = *equipment under proactive maintenance plan*
d_p = *desired equipment under proactive plan*
b = *perceived percentage of broken equipment to a normal percentage*
s_a = *staff availability for proactive repair*
m_b = *multiplier from broken equipment on desired equipment under proactive plan*
m_s = *multiplier from staff availability on desired equipment under proactive plan*
t_{rp} = *transfer of equipment from reactive to proactive plan*
T_p = *time to adjust equipment under proactive plan*

Then the equation for transfer of equipment to proactive plan is as follow:

$$t_{rp} = (d_p - e_p) / T_p \qquad (3)$$

$$d_p = m_b(b) \cdot m_s(S_a) \cdot e_p \qquad (4)$$

Where e_p is derivative of e_p over time and m_b and m_s are increasing functions of

b and s_a respectively. *Desired equipment under proactive plan* reacts to the condition of broken equipment and staff availability. When *perceived broken equipment* or *maintenance staff availability* increase, *desired equipment under proactive maintenance increases* and *equipment under proactive maintenance plan* moves toward the desired value according to equation 3.

4. BEHAVIOR IN REACTIVE MODE

This section examines the behavior of the system under reactive decision making[3]. In order to see the impact of different feedback loops, 3 feedback loops discussed in the previous section are gradually activated in the computer simulations and the resultant system behavior is discussed.

4.1 Behavior of the model with reactive decision making about maintenance staff

In the simulation presented in this section, only maintenance staff is changed in reaction to the *perceived percentage of broken equipment*. Management does not change *equipment under proactive maintenance* in reaction to the shortage or excess of maintenance staff or in reaction to percentage of broken equipment. To create this test condition, feedback loops 2 and 3 are disconnected.[4]

Figures 7.1 and 7.2 show the behavior of the system under the above test conditions when only feedback loop 1 of the three major feedback loops is active. The system oscillates with a periodicity of about six years. As is shown in Figure 7.1, *equipment under proactive maintenance plan* does not change much relative to the changes in *equipment under reactive maintenance plan*, which oscillates with an amplitude of about 10 percent of its average value. As is shown in Figure 7.1 the rate of *transfer of equipment to proactive plan* is zero because that rate can only change due to change in staff availability, through loop 3, or change in percentage of broken equipment through loop 2. Since both loops 2 and 3 are not active, *transfer of equipment to proactive plan* remains zero during the simulation. The minor oscillation of *equipment under proactive maintenance plan* is due to the changes in the rate of reactive and proactive repairs of the equipment under that plan as well as changes in the rate at which equipment are taken for preventive repair; variations in all three rates are due to changes in maintenance staff. *Maintenance staff* and *percentage of equipment operating* oscillate with the same periodicity of six years and with about a one year lead in *maintenance staff*.

Figure 7.2 shows some of the major elements of feedback loop 1 that are generating the oscillation. When *equipment under reactive maintenance plan* increases, after a delay, break–down of equipment goes up and raises the percentage of broken equipment. Eventually after a delay, as shown in Figure 7.2, *perceived percentage of broken equipment* rises and causes the *maintenance staff* to increase with some delay. As *maintenance staff* rises, so does reactive repair of equipment. Increase in *reactive repair* slows down the growth of *equipment under reactive repair*, shown in Figure 7.1, and finally *equipment under reactive repair* picks up at around year 23 and falls there-after. As *equipment under reactive repair*, representing broken equipment, falls, percentage of equipment broken drops too. However, it takes some time for management to perceive the

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[3] To run the model under reactive mode, in the equations of the model Switch to Activate Proactive Policy (SAPP) is set equal to zero.

[4] To disconnect feedback loops 2 and 3, two switches are set zero. As *switch to activate the effect of staff availability* is set at zero, loop 3 will be disconnected. A value of zero for the *switch to activate the effect of broken equipment on proactive plan* disconnects loop 2.

change in percentage of broken equipment and act on it. So *perceived percentage of broken equipment* picks and falls at about year 24 in Figure 7.2, with one year delay relative to *equipment under reactive repair*, and the causality chain begins to work in a reverse direction and a new part of the cycle starts.

When management changes the maintenance staff in reaction to plant condition, such a reactive mode of operation by itself will generate oscillation. In the next section, the behavior of the model will be examined when the reactive mode is extended to include changes in the coverage of preventive maintenance plans due to changes in the percentage of broken equipment.

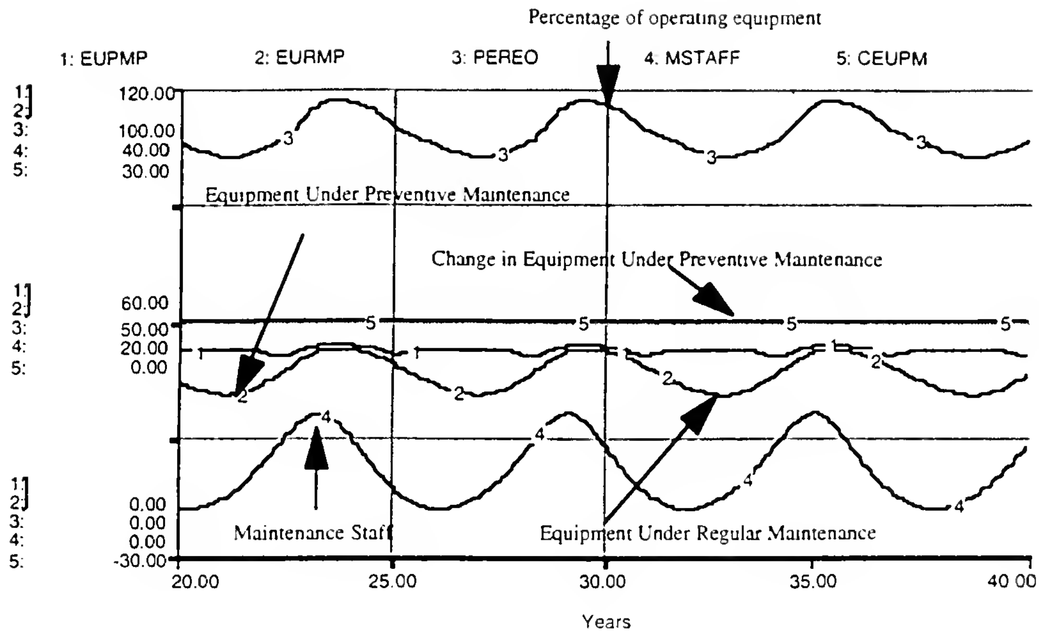

Figure 7.1: Behavior of the model when feedback loops 2 and 3 are disconnected.

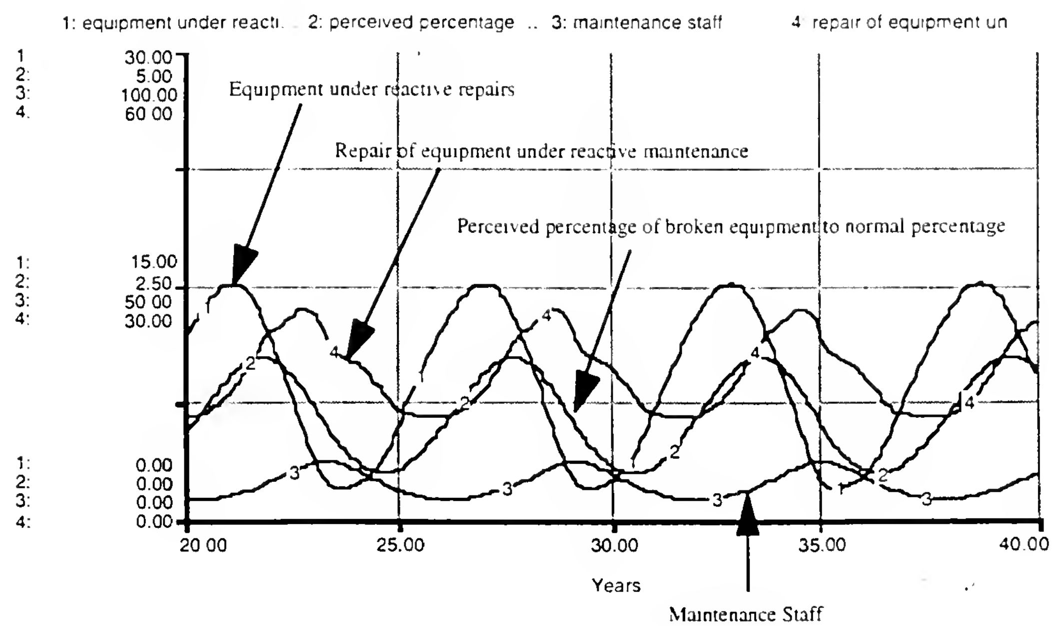

Figure 7.2: Behavior of some elements of feedback loop 1 when feedback loops 2 and 3 are disconnected.

4.2 *Behavior of the model when PM plan reacts to broken equipment*

This section examines the behavior of the model when in addition to feedback loop 1, feedback loop 2 is also activated. Under this new condition, the reactive decision making is extended to include a reactive change in the coverage of proactive maintenance plan in response to the percentage of broken equipment. In order to activate this condition in the model, the *switch to activate the effect of broken equipment on proactive plan* is set at 1. Figures 8.1 and 8.2 show the behavior of the model.

The system oscillates with a periodicity of about five years. As is shown in Figure 8.1, *equipment under proactive maintenance* and *equipment under reactive maintenance* oscillate in opposite directions with an amplitude wider than the oscillation in figure 7.1. *Percentage of operating equipment* and *maintenance staff* oscillate with the same periodicity of five years and are almost in phase with the oscillation of *equipment under preventive maintenance.* When the number of staff increases so does *percentage of operating equipment* and *equipment under proactive maintenance.* The amplitudes of oscillation of equipment under different maintenance are about 20 percent of their average value.

Figure 8.2 shows some of the major elements of feedback loop 2 that accentuates the oscillation of the system. As is depicted in Figure 8.2, when *equipment under reactive repair*, representing broken equipment, increases, so does *perceived percentage of broken equipment* with some -perception delay. The *perceived percentage of broken equipment* is the percentage of broken equipment relative to a normal percentage. However, as perceived percentage of broken equipment increases and equipment maintenance becomes a hot issue, management reacts and increases the *equipment under proactive maintenance plan* as shown in Figure 8.2. As *equipment under proactive maintenance plan* rises, *equipment under reactive maintenance,* shown in Figure 8.1, drops, and as a result less equipment breaks and *perceived percentage of broken equipment* drops more than the previous run. Then, management reaction to decrease maintenance staff will be stronger than in the previous run. This stronger reaction accentuates the oscillation created by feedback loop 1.

In summary, as loop 2 strengthens the reactive mode of management by changing the coverage of proactive maintenance plan in reaction to the condition of equipment, the oscillatory behavior of the system increases. The next section will add some more reactive force to the system and examine the resultant behavior.

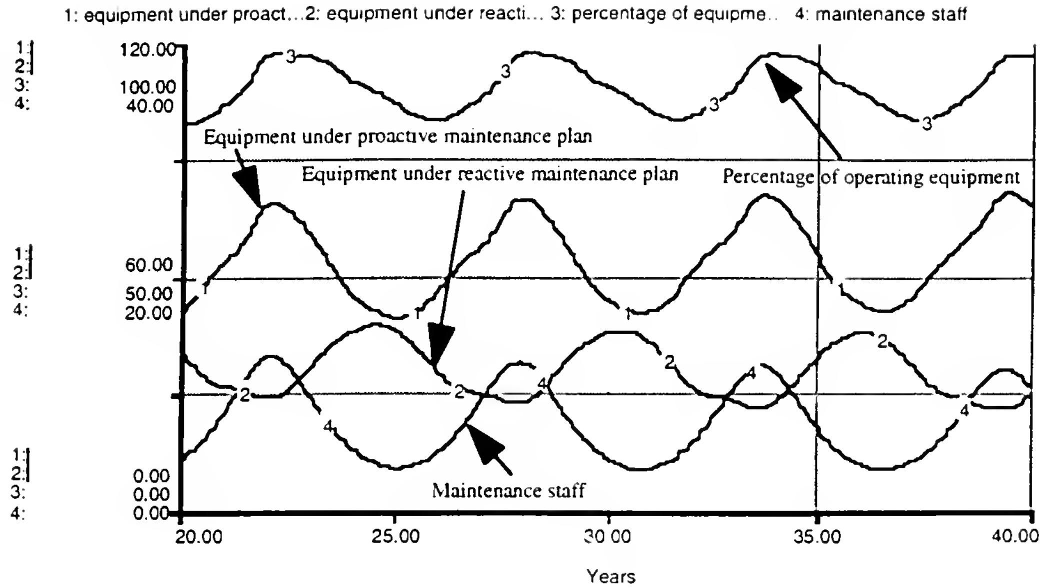

Figure 8.1: Behavior of the system when feedback loop 3 is disconnected.

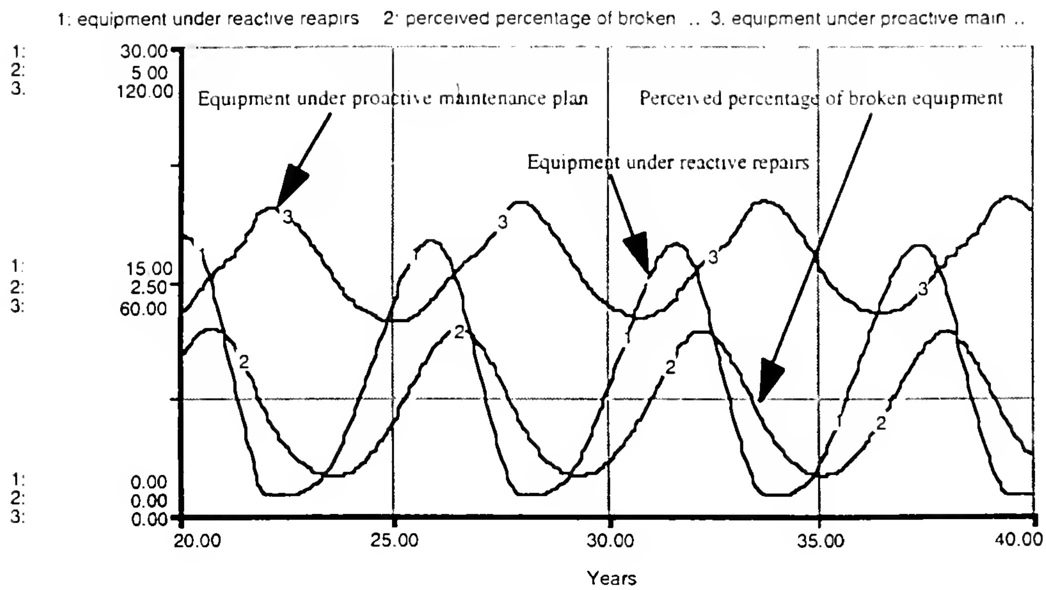

Figure 8.2: Behavior of some elements of feedback 2 when feedback loop 3 is disconnected.

4.3 Behavior of the model when PM plan reacts to availability of staff

This section examines the behavior of the model when in addition to loops 1 and 2, loop 3 is activated too. To activate loop 3 in the model, a switch called *switch to activate the effect of staff availability* is set equal to one in the model. Under this new condition, the reactive mode of management is extended farther and the coverage of preventive

maintenance plan changes in reaction to the availability of maintenance staff too. Figures 9.1 and 9.2 show the behavior of the model.

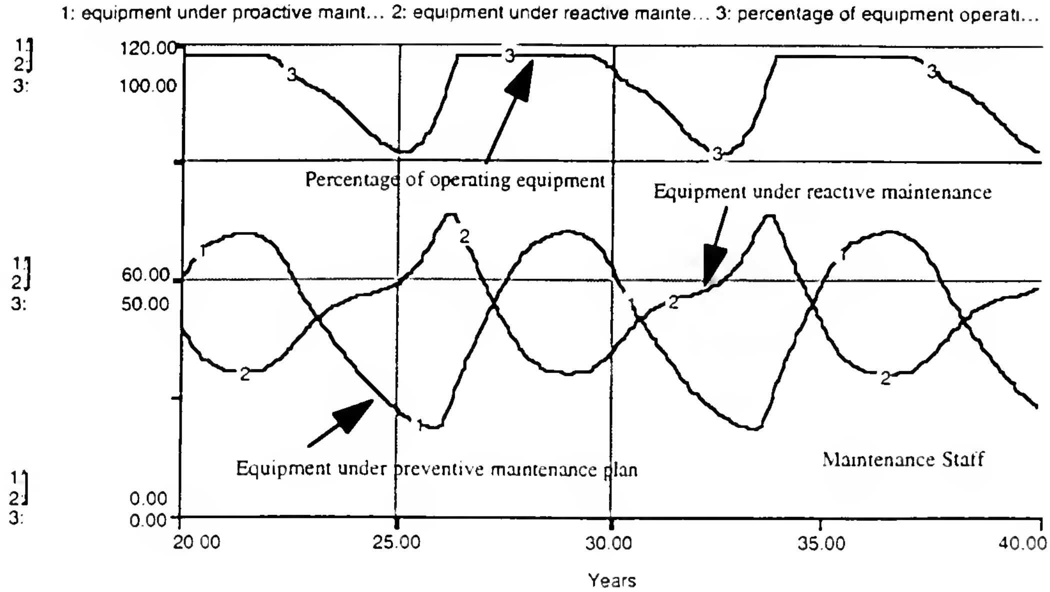

Figure 9.1: Behavior of the system under reactive mode when three feedback loops 1, 2, and 3 are active.

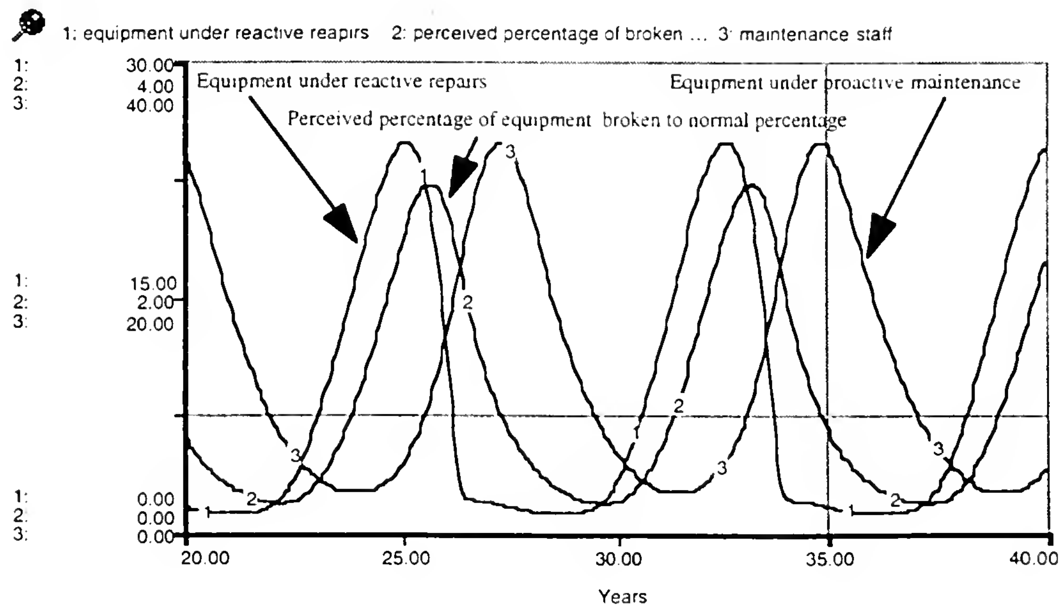

Figure 9.2: Behavior of some elements of feedback loop 3 under reactive mode when all feedback loops are active.

The system oscillates with a periodicity of about seven years. As is shown in Figure 9.1, the amplitude of oscillation is much wider than the previous run. *Equipment under proactive maintenance plan* oscillates with an amplitude of about 50 percent of its

average value. *Percentage of operating equipment* oscillates and drops from its maximum of about 97 percent to less than 80 percent. When *maintenance staff* rises, the rate of repair increases and after the repair rate becomes more than the breaking rate, *percentage of operating equipment*, shown in Figure 9.1, increases and the *equipment under reactive repairs*, shown in Figure 9.2, drops. As *equipment under reactive repairs* drops and more staff become available, proactive maintenance expands and the *equipment under proactive maintenance plan* rises. But as more equipment comes under the proactive maintenance plan, less equipment will break and *perceived percentage of broken equipment* drops to very low levels, causing management to react and decrease the *maintenance staff* in order to cut costs and raise the profit in the short run.

Figure 9.2 shows some of the elements of feedback loop 3 which accentuates the reactive mode of management and it resultant oscillatory behavior. As is shown in Figure 9.2, when *equipment under reactive repairs* and *perceived percentage of broken equipment* are rising from the beginning of simulation for three to four years, *staff availability for proactive repairs*, not shown in the figures, decreases to very low values. When *staff availability for proactive repairs* decreases, all the equipment under the proactive maintenance plan can not be taken for –proactive repair on schedule. As a result, more equipment comes under reactive maintenance, breakdown rates and percentages of broken equipment increases. Rise in broken equipment makes management react with more strength to increase maintenance staff to the higher level in Figure 9.1 relative to Figure 8.1. When finally, addition of maintenance staff increases the repair rate over the breakdown rate of equipment, then *equipment under reactive repair* falls and excess maintenance staff appears. *Staff available for Proactive maintenance*, not shown in Figure 9.2, rises sharply. As a result, while *equipment under reactive repair* is low, *equipment under proactive maintenance* rises to a high value and *equipment under reactive maintenance*, shown in Figure 9.1, and broken equipment drop to low values. As management reacts to the low value of broken equipment and decreases maintenance staff, a new cycle starts.

In summary, the new reactive force in loop 3 accentuates the oscillation. When, due to other reactive policies, broken equipment rises and there is a shortage of maintenance staff, repair of broken equipment has priority, proactive maintenance is ignored, and the coverage of proactive maintenance declines. As equipment under proactive maintenance decreases and more equipment ~~be~~comes under reactive maintenance, the breakdown rate of equipment rises and increases the amount of broken equipment which in turn worsens the shortage of maintenance staff. As management reacts and increases the staff to take care of the extra backlog of broken equipment, backlog drops and extra staff expands preventive maintenance and, as a result, brings the broken equipment to a very low level. In a reactive mode, the low level of broken equipment causes management to react and decrease maintenance staff to cut costs and raise profit in the short run. This reaction makes the system to go back to a high level of broken equipment.

Oscillation of the maintenance system and instability in availability of equipment are not desirable. Such oscillation creates disruption in production and products delivery, it causes personnel instability, and it increases the maintenance costs during high breakdown rates. But reactive policies that create the oscillation are self supporting in the short run, as they seem decisively to work with a short term perspective.

Figures 10.1 and 10.2 show two sections of the behavior shown in Figure 9.1 when all reactive policies are active. Figure 10.1 shows the behavior from Year 23 to 27 and Figure 10.2 shows the behavior from Year 27 to 31. In Figure 10.1, after Year 23, *percentage of operating equipment* and *equipment under proactive maintenance plan* are falling and equipment availability is deteriorating. As a result, –management reacts and starts to increase maintenance staff from Year 24. As maintenance staff rises, decline of

operating equipment slows down. Equipment availability reaches its lowest value in Year 25. After Year 25, *percentage of operating equipment* starts to rise. One year later, in Year 26, while operating equipment is still rising and the plant is overcoming its maintenance crisis, *equipment under Proactive maintenance* begins to increase too. By the year 27, reactive policies have done the work and *percentage of operating equipment* is very high and most of the equipment are under proactive maintenance. Three years experience from Year 24 to Year 27 support the reactive policies and the mental models behind it. However, what a system perspective shows is that the very successful experience of the years 24 to 27, create the foundation of another reactive move which starts after Year 27 and is shown in Figure 10.2.

As shown in Figure 10.2, in Year 27 percentage of operating equipment is quite high, maintenance crisis is over, preventive maintenance is rising and maintenance staff who have repaired the huge backlog of broken equipment is still a little rising. Pressures to cut cost and good working conditions of the equipment make the management to decrease maintenance staff. So around the second quarter of Year 27, staff is decreased to cut costs. But until Year 29, in spite of a decline in staff, operating equipment stays high and even *equipment under proactive maintenance plan* increases, and the reactive cost cut efforts look very successful. So management keeps decreasing the maintenance staff.

But, inadequacy of staff appears to have its impact on the system after Year 29 when equipment under proactive maintenance starts to fall and, after some delay, towards the end of Year 29, operating equipment starts to drop. Cost cut efforts continue and staff keeps falling until Year 30, when operating equipment drops to less than 90 percent, indicating a sign of crisis. As a result, the decline of maintenance staff slows down or stops. Reactive policies will make the system turn around to take care of broken equipment by increasing the staff.

The next section examines a proactive policy to cure this undesirable behavior.

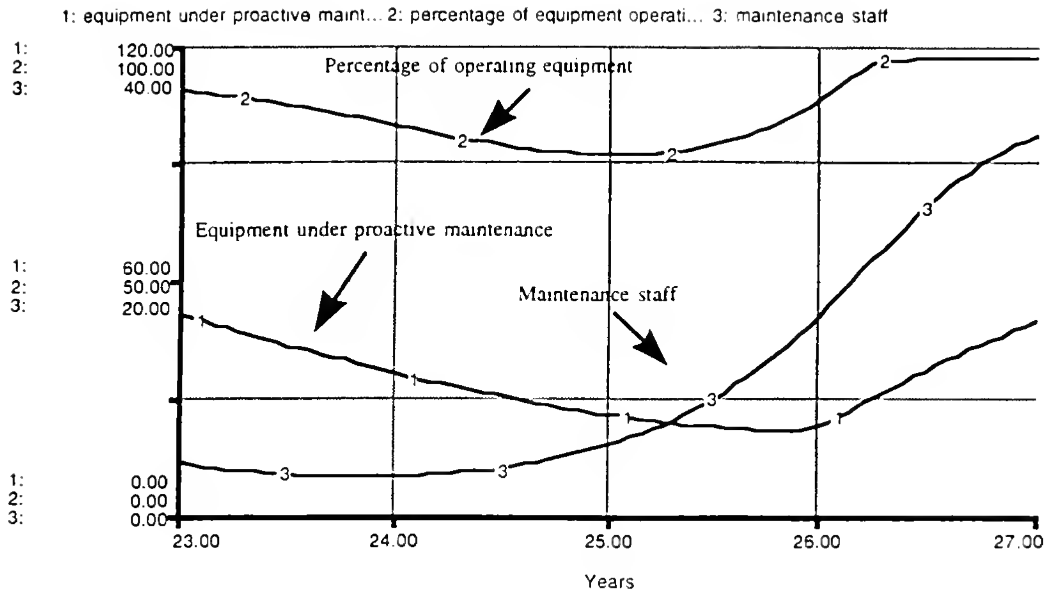

Figure 10.1: Reactive policies seem to work in the short run:
maintenance staff is raised in reaction to low percentage of operating equipment.

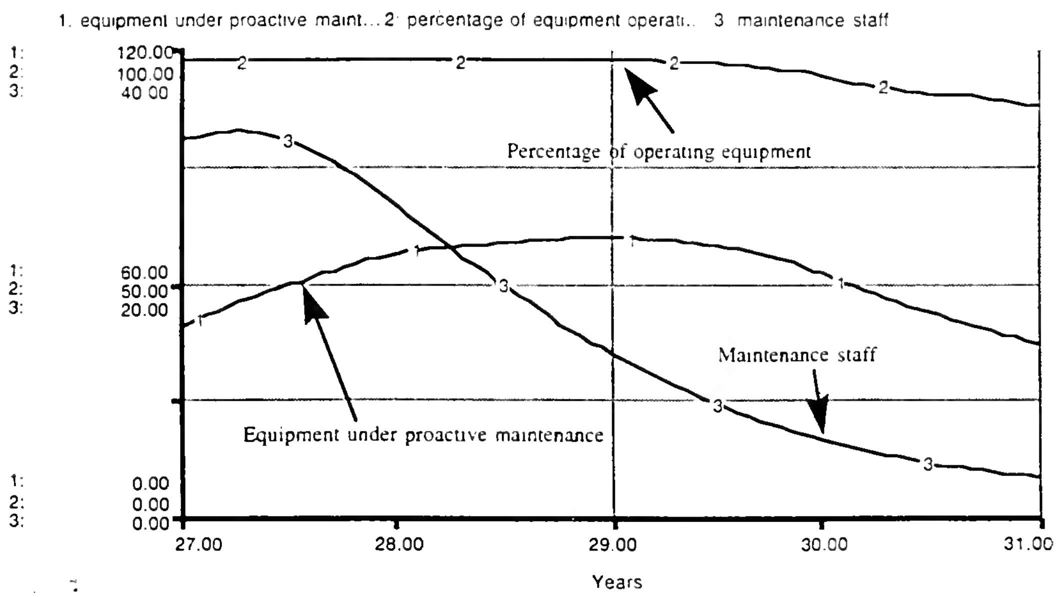

Figure 10.2: Reactive policies seem to work in the short run:
maintenance staff is decreased to cut costs without much short run consequences.

5. PROACTIVE POLICY FOR A NON OSCILLATORY BEHAVIOR

In this section, management policies governing two major decisions are changed from reactive to proactive mode. The major decisions are concerned with change in maintenance staff and change in equipment under preventive maintenance. First the new decision rules are explained and then the consequent behavior is analyzed.

5.1 Proactive decision rule to change maintenance staff:

Under proactive policy, *desired maintenance staff* is set equal to the required staff to do proactive and reactive repairs. Management is not reacting to pressures to cut costs or decrease the percentage of broken equipment. Desired maintenance staff is driven by the need of the maintenance department to do its maintenance job. Suppose that:

e_{pr} = *equipment under proactive repairs [equipment]*

e_{rr} = *equipment under reactive repairs [equipment]*

s_{pr} = *staff time required to do proactive repairs on one unit of equipment [person-year]*

s_{rr} = *staff time required to do reactive repairs on one unit of equipment [person-year]*

d = *desired maintenance staff [person]*

r_p = *required staff for proactive maintenance [person]*

r_r = *required staff for reactive maintenance [person]*

n_p = *normal time to finish proactive maintenance [year]*

n_r = *normal time to finish reactive maintenance [year]*

Then the proactive policy equations for *desired maintenance staff* are:

$$d = r_p + r_r \qquad (5)$$

$$r_p = s_{pr} \cdot e_{pr} / n_p \qquad (6)$$

$$r_r = s_{rr} \cdot e_{rr} / n_r \qquad (7)$$

After *desired maintenance staff* is determined by equation 5, then equation 1 is used to adjust *maintenance staff* to its desired value.

5.2 Proactive decision rule to change equipment under preventive repair

In proactive mode, all the equipment is put under the preventive maintenance plan without reacting to the condition in the system. In another words, under all conditions the system strives towards bringing all the equipment under the preventive maintenance plan.

e_r = *equipment under reactive maintenance plan*

t_{rp} = *transfer of equipment from reactive to proactive plan*

t_{rp} = *transfer of equipment from reactive to proactive plan*

T_p = *time to adjust equipment under proactive plan*

$$t_{rp} = e_r / T_p$$

5.3 Behavior under proactive management

Figure 11 shows the behavior of the system under the proactive policy. As Figure 11 shows, the system starts from the same initial conditions as in the previous sections, but it does not oscillates. *Equipment under reactive maintenance* decreases to zero while *equipment under proactive maintenance plan* moves to its maximum value to cover all the operating equipment. *Percentage of equipment operating* does not fall and remains high -- close to 100 percent. *Maintenance staff* does not rise or oscillate, it drops from its initial value to its equilibrium level, which is adequate to maintain all the equipment under the proactive maintenance plan.

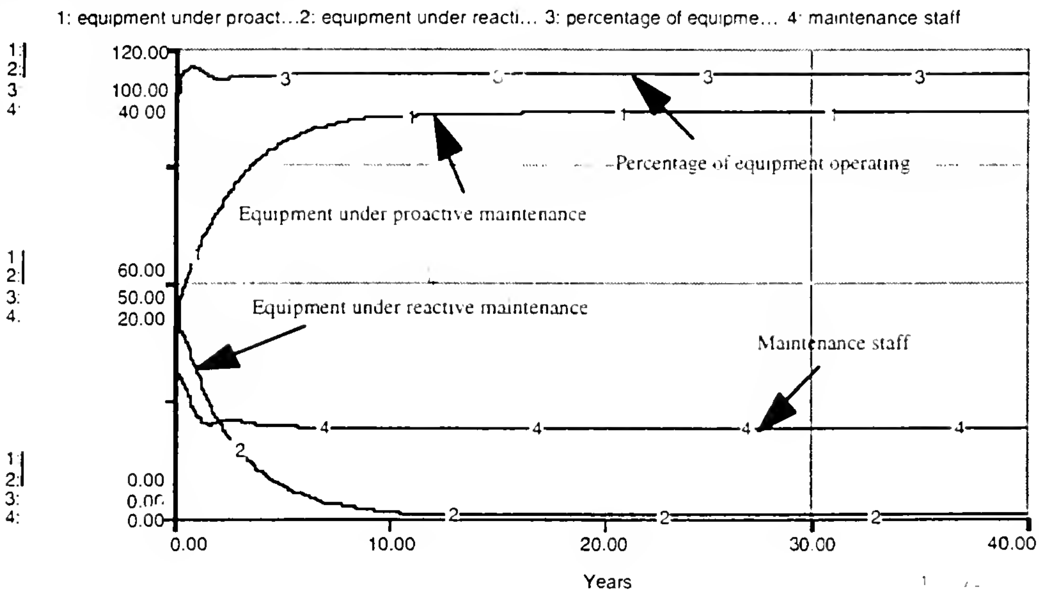

Figure 11: Behavior of the model under proactive policy.

Under the new policy, management does not operate in a reactive mode to create oscillation. Instead, an objectives is set to move all the equipment out of reactive maintenance plan and also provide all the required staff to do the maintenance job on time. The system is led towards those goals. Figure 11 shows the behavior of *maintenance s*taff and *equipment under proactive maintenance.* As is shown in Figure 11, under a proactive policy, *equipment under reactive maintenance* moves to a zero value as its fixed goal and as a result all equipment is moved to the proactive plan. *Desired maintenance staff* is set equal to the required staff to do proactive and preventive repairs. Since all the equipment is transferred to the proactive plan, the *desired maintenance staff* approaches a constant value and *maintenance staff,* as shown in Figure 11, approaches a stable value that is adequate to do all the maintenance work on time.

The result of the proactive policy is high uptime with stable and, on average, lower maintenance staff. Figures 12.1 and 12.2 show the accumulated staff time and

in both simulations the model starts from the same initial conditions. As is shown in Figure 11.1, under the proactive policy, accumulated non-operating equipment is much lower than reactive policies. This means under a proactive policy, more equipment is operational during the simulation period. Figure 11.2 shows that the accumulated staff time used to maintain the plants is lower under a proactive policy relative to the reactive mode. Under a proactive mode, while the plant is very stable in terms of operating equipment and maintenance staff, less resources are used to keep the plant stable with a higher equipment uptime. Under reactive policies, when the backlog of broken equipment is high and a maintenance crisis occurs, maintenance staff rises too high and too fast to repair the high accumulation of broken equipment. As high backlogs of broken equipment are depleted, maintenance staff is higher than required and there is some excess staff time until reactive policies decrease the extra staff. Accumulation of excess staff after the crisis creates a higher accumulated staff time for the reactive policies during simulation. In addition, it takes more resources to perform reactive repair than to do proactive repair, where mostly tools and parts can be prepared according to pre-planned repair work. Under reactive policies, as maintenance staff declines too low to cut costs, the backlog of broken equipment rises again. High backlogs of broken equipment during maintenance crises make the accumulated non-operating equipment higher for the reactive policies relative to the proactive policies.

6. CONCLUSION

Fragmentation, or a lack of systems thinking, combined with reactiveness cause the proactive maintenance programs to cease to operate. Functioning under management characterized by reactiveness and fragmentation, maintenance programs can oscillate between reactive and proactive maintenance. Since reactive decision making usually leads to short run results, the decisions become self approving and the causal linkages to the long run consequences are ignored. Self approving reactive actions are not conducive to learning, and actually become a barrier to learning. Fragmentation does not allow the full consequences of reactive actions to be appreciated. In order to understand the flaws of reactive decisions, a system perspective is necessary. With a system perspective, consequences of reactive actions that occur far from the action point in both time and space can be better understood. Such an understanding improves the decision makers' mental models and facilitates learning.

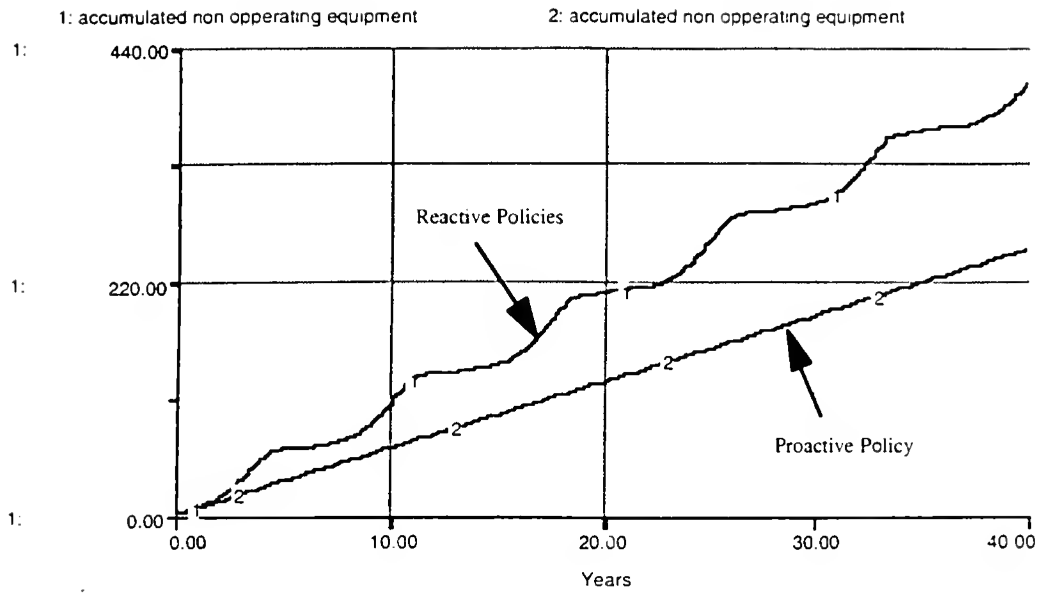

Figure 12.1 : Accumulated non-operating equipment under different policies.

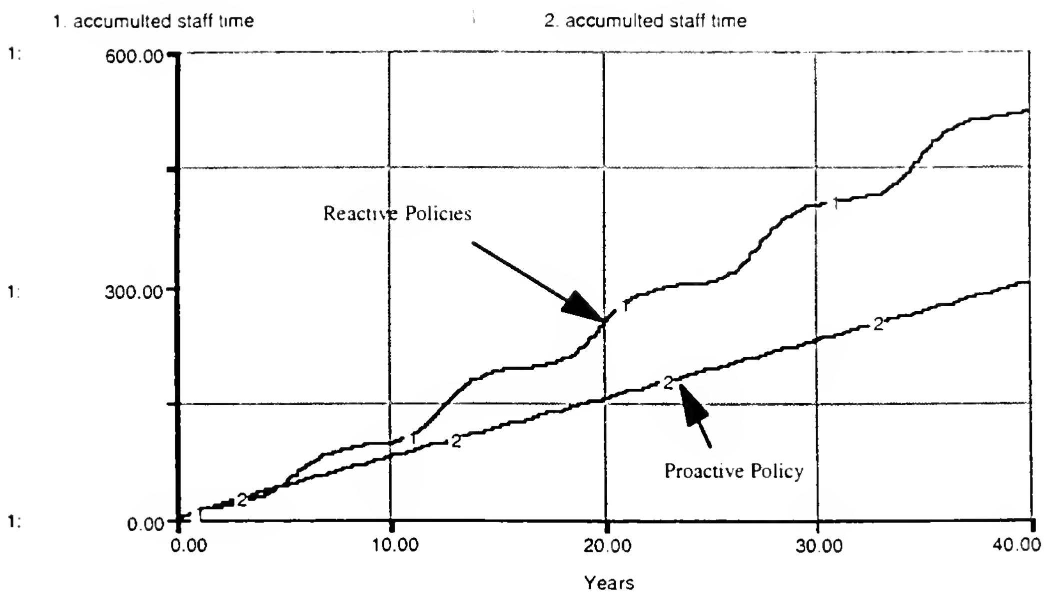

Figure 12.2 : Accumulated maintenance staff time under different policies.

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Appendix:

Model's equations:

accumulated_non_opperating_equipment(t) = accumulated_non_opperating_equipment(t - dt) + (non_operating_equipment) * dt
INIT accumulated_non_opperating_equipment = 0

DOCUMENT: Accumulated non operating equipment calculates total equipment that are not up and operating during the simulation (Equipment-year)

INFLOWS:
non_operating_equipment = total_equipment-total_operating_equipment
DOCUMENT: Non-operating equipment measures those equipment that are operating at each moment of time (Equipment)

accumulted_staff_time(t) = accumulted_staff_time(t - dt) + (staff_time) * dt
INIT accumulted_staff_time = 0

DOCUMENT: Accumulated staff time measures the amount of maintenance staff time that are available during the simulation as an indication of total resources spent on maintenance (staff-year)

INFLOWS:
staff_time = maintenance_staff
DOCUMENT: Maintenance staff (staff)

equipment_under_proactive_maintenance(t) = equipment_under_proactive_maintenance(t - dt) + (equipment_transfer_to_do_proactive_maintenance - proactive_maintenance_completed) * dt
INIT equipment_under_proactive_maintenance = .1 equipment_under_proactive_maintenance_plan

DOCUMENT: Equipment under proactive maintenance repesents those equipment that are taken away from operation to do proactive maintenance (Equipment)

INFLOWS:
equipment_transfer_to_do_proactive_maintenance = multiplier_from_staff_availability_on_transfer_to_proactive_rep*(equipment_under_proactive_maintenance_plan/time_to_take_equipment_for_proactive_maintenance)
DOCUMENT: Equipment that are moved from operation to do proactive maintenance on them [Equipment/Year]

OUTFLOWS:
proactive_maintenance_completed = multiplier_from_staff_availability_on_proactive__repair*equipment_under_proactive_maintenance/normal_proactive_repair_time
DOCUMENT: Proactive maintenance completed per year represents the number of equipments that are proactively repaired and are transfered back to operation (Equipment/Year)

equipment_under_proactive_maintenance_plan(t) = equipment_under_proactive_maintenance_plan(t - dt) +

(transfer_of_equipment_to_proactive_plan + reactive_repair_of_equipment_under_proactive_plan + proactive_maintenance_completed - break_down_of_equipment_under_proactive_maintenance - equipment_transfer_to_do_proactive_maintenance) * dt
INIT equipment_under_proactive_maintenance_plan = 50

DOCUMENT: Equipment under proactive maintenance plan represents the number of equipment that are proactively maintained [Equipment]

INFLOWS:
transfer_of_equipment_to_proactive_plan = (1-switch_to_activate_the_proactive_policy)*(desired_equipment_under_proactive_maintenance-equipment_under_proactive_maintenance_plan)/time_to_transfer_equipment_to_proactive_plan+switch_to_activate_the_proactive_policy*equipment_under_reactive_maintenance_plan/time_to_transfer_equipment_to_proactive_plan
DOCUMENT: transfer of equipment to proactive plan represent the number of equipment that are transfered from reactive maintenance to proactive maintenance plan [Equipment/Year]

reactive_repair_of_equipment_under_proactive_plan = (break_down_of_equipment_under_proactive_maintenance/(break_down_of_equipment_under_reactive_maintenance+break_down_of_equipment_under_proactive_maintenance))*(equipment_under_reactive_reapirs/normal_reactive_repair_time)*multiplier_from_staff_availability_on_reactive_repair
DOCUMENT: Repair of equipment under proactive maintenance represents the amount of equipments that were under proactive plan but broke and are now proactively repaired and are moving back to operation [Equipment/Years]

proactive_maintenance_completed = multiplier_from_staff_availability_on_proactive__repair*equipment_under_proactive_maintenance/normal_proactive_repair_time
DOCUMENT: Proactive maintenance completed per year represents the number of equipments that are proactively repaired and are transfered back to operation (Equipment/Year)

OUTFLOWS:
break_down_of_equipment_under_proactive_maintenance = percentage_of_break_down_of_eq_under_proactive_plan_per_year*equipment_under_proactive_maintenance_plan
DOCUMENT: Equipment under proactive maintenance plan break down rate [Equipment/Year]

equipment_transfer_to_do_proactive_maintenance = multiplier_from_staff_availability_on_transfer_to_proactive_rep*(equipment_under_proactive_maintenance_plan/time_to_take_equipment_for_proactive_maintenance)
DOCUMENT: Equipment that are moved from operation to do proactive maintenance on them [Equipment/Year]

equipment_under_reactive_maintenance_plan(t) = equipment_under_reactive_maintenance_plan(t - dt) + (repair_of_equipment_under_reactive_maintenance - transfer_of_equipment_to_proactive_plan - break_down_of_equipment_under_reactive_maintenance) * dt
INIT equipment_under_reactive_maintenance_plan = 50

DOCUMENT: Equipment under reactive maintenance plan [Equipment]

INFLOWS:
repair_of_equipment_under_reactive_maintenance = (break_down_of_equipment_under_reactive_maintenance/(break_down_of_equipment_under_reactive_maintenance+break_down_of_equipment_under_proactive_maintenance))*(equipment_under_reactive_reapirs/normal_reactive_repair_time)*multiplier_from_staff_availability_on_reactive_repair

DOCUMENT: Repair of equipment under reactive maintenance represents the amount of equipment that were under reactive plan and broke, are repaired, and are transfering back to operation [Equipment/Year]. It is assumed that the ratio of the repaired equipment that should go to equipment under reactive maintenance is the same as the ratio of break down from equipment under reactiveplan to total break down.

OUTFLOWS:
transfer_of_equipment_to_proactive_plan = (1-switch_to_activate_the_proactive_policy)*(desired_equipment_under_proactive_maintenance-equipment_under_proactive_maintenance_plan)/time_to_transfer_equipment_to_proactive_plan+switch_to_activate_the_proactive_policy*equipment_under_reactive_maintenance_plan/time_to_transfer_equipment_to_proactive_plan

DOCUMENT: transfer of equipment to proactive plan represent the number of equipment that are transfered from reactive maintenance to proactive maintenance plan [Equipment/Year]

break_down_of_equipment_under_reactive_maintenance = percentage_of_eq_break_down_per_year_under_reactive_plan*equipment_under_reactive_maintenance_plan

DOCUMENT: Equipment under reactive maintenance break down rate [Equipment/Year]

equipment_under_reactive_reapirs(t) = equipment_under_reactive_reapirs(t - dt) + (break_down_of_equipment_under_reactive_maintenance + break_down_of_equipment_under_proactive_maintenance - reactive_repair_of_equipment_under_proactive_plan - repair_of_equipment_under_reactive_maintenance) * dt

INIT equipment_under_reactive_reapirs = .1*equipment_under_reactive_maintenance_plan+0*equipment_under_proactive_maintenance_plan

DOCUMENT: Equipment under reactive repair [Equipment]

INFLOWS:
break_down_of_equipment_under_reactive_maintenance = percentage_of_eq_break_down_per_year_under_reactive_plan*equipment_under_reactive_maintenance_plan

DOCUMENT: Equipment under reactive maintenance break down rate [Equipment/Year]

break_down_of_equipment_under_proactive_maintenance = percentage_of_break_down_of_eq_under_proactive_plan_per_year*equipment_under_proactive_maintenance_plan

DOCUMENT: Equipment under proactive maintenance plan break down rate [Equipment/Year]

OUTFLOWS:

reactive_repair_of_equipment_under_proactive_plan = (break_down_of_equipment_under_proactive_maintenance/(break_down_of_equipment_under_reactive_maintenance+break_down_of_equipment_under_proactive_maintenance))*(equipment_under_reactive_reapirs/normal_reactive_repair_time)*multiplier_from_staff_availability_on_reactive_repair

DOCUMENT: Repair of equipment under proactive maintenance represents the amount of equipments that were under proactive plan but broke and are now proactively repaired and are moving back to operation [Equipment/Years]

repair_of_equipment_under_reactive_maintenance = (break_down_of_equipment_under_reactive_maintenance/(break_down_of_equipment_under_reactive_maintenance+break_down_of_equipment_under_proactive_maintenance))*(equipment_under_reactive_reapirs/normal_reactive_repair_time)*multiplier_from_staff_availability_on_reactive_repair

DOCUMENT: Repair of equipment under reactive maintenance represents the amount of equipment that were under reactive plan and broke, are repaired, and are transfering back to operation [Equipment/Year]. It is assumed that the ratio of the repaired equipment that should go to equipment under reactive maintenance is the same as the ratio of break down from equipment under reactiveplan to total break down.

maintenance_staff(t) = maintenance_staff(t - dt) + (change_in_maintenance_staff) * dt

INIT maintenance_staff = staff_time_to_finish_proactive_maintenance*equipment_under_proactive_maintenance/normal_proactive_repair_time+staff_time_required_to_complete_reactive_repair*equipment_under_reactive_reapirs/normal_reactive_repair_time

DOCUMENT: Maintenance staff [Person]

INFLOWS:

change_in_maintenance_staff = (desired_maintenance_staff-maintenance_staff)/time_to_adjust_maintenance_staff

DOCUMENT: Change in maintenance staff [Person/Year]

available_staff_for_proactive_maintenance = maintenance_staff*reqired_staff_for_proactive_repair/(reqired_staff_for_proactive_repair+required_staff_for_reactive_repair)

DOCUMENT: Available staff for proactive maintenance [Person]. It is assumed that there is no priority to in allocation of staff between reactive and proactive maintenance.

available_staff_for_reactive_repair = maintenance_staff*required_staff_for_reactive_repair/(required_staff_for_reactive_repair+reqired_staff_for_proactive_repair)

DOCUMENT: Avaialable staff for reactive repair [Person]

desired_equipment_under_proactive_maintenance = MIN((switch_to_activate_the_effect_of_staff_availability*multiplier_from_staff_availability_on_proactive_plan+1-switch_to_activate_the_effect_of_staff_availability)*equipment_under_proactive_maintenance_plan*(1-switch_to_activate_the_effect_of_broken_equ_on_proactive_plan+switch_to_activate_the_effect_of_broken_equ_on_proactive_plan*multiplier_from_broken_equipment_on_proacti

ve_plan),total_operating_equipment)

DOCUMENT: Desired equipment under proactive maintenance represents management goal for the coverage of proactive plan [Equipment]

desired_maintenance_staff = (1-switch_to_activate_the_proactive_policy)*maintenance_staff*multiplier_from_broken_equipment_on_desired_maintenance_staff+switch_to_activate_the_proactive_policy*(reqired_staff_for_proactive_repair+required_staff_for_reactive_repair)

DOCUMENT: Desired maintenance staff to carry out both reactive repair and proactive maintenance [Persons]

normal_percentage_of_broken_equipment = normal_reactive_repair_time*percentage_of_eq_break_down_per_year_under_reactive_plan

DOCUMENT: Normal percentage of broken equipment [Fraction]

normal_proactive_repair_time = 1

DOCUMENT: Normal proactive repair time represents the average amount of time necessary to do proactive time on one unit of equipment [Year]

normal_reactive_repair_time = 2

DOCUMENT: Normal reactive repair time represents the avaerage amount of time necessary to do reactive repair on one unit of equiment [Year]

perceived_percentage_of_broken_equipment_ratio = SMTH1(percentage_of_broken_equipment,time_to_perceive_percentage_of_broken_equipment)/normal_percentage_of_broken_equipment

DOCUMENT: Perceived percentage of broken equipment [Fraction]

percentage_of_break_down_of_eq_under_proactive_plan_per_year = .05

DOCUMENT: Percentage of brake down of equipment under proactive maintenance represents the normal break down of equipment per year [Fraction/Year]

percentage_of_broken_equipment = equipment_under_reactive_reapirs/(equipment_under_proactive_maintenance_plan+equipment_under_reactive_maintenance_plan)

DOCUMENT: This variable represents the percentage of equipment broken and under reactive repair [Fraction]

percentage_of_equipment_operating_at_each_moment_of_time = 100*(equipment_under_reactive_maintenance_plan+equipment_under_proactive_maintenance_plan)/total_equipment

DOCUMENT: Percentage of equipment operating at any moment of time (Percent)

percentage_of_eq_break_down_per_year_under_reactive_plan = .4

DOCUMENT: Percentage of equipment break down per year under a reactive plan represents an average percentage for the break down [Fraction/ Year]

percentage_of_operating_equipment = 100*(1-

accumulated_non_opperating_equipment/(total_equipment*TIME))
DOCUMENT: Average percentage of equipment operating from the beginning of the simulation up to the current time [Percentage]

reqired_staff_for_proactive_repair = staff_time_to_finish_proactive_maintenance*equipment_under_proactive_maintenance/normal_proactive_repair_time
DOCUMENT: Required repair staff for proactive maintenance [Person]

required_staff_for_reactive_repair = staff_time_required_to_complete_reactive_repair*equipment_under_reactive_reapirs/normal_reactive_repair_time
DOCUMENT: Required staff for reactive repair on broken equipment [Person]

staff_availability_for_proactive__repair = available_staff_for_proactive_maintenance/reqired_staff_for_proactive_repair
DOCUMENT: Staff availability ratio for proactive maintenance [Fraction]

staff_time_required_to_complete_reactive_repair = .24
DOCUMENT: Staff-time required to complete reactive repair on a unit of broken equipment [Person-year/Equipment]

staff_time_to_finish_proactive_maintenance = .12
DOCUMENT: Staff time required to do proactive maintenance on a unit of equipment [Person-year/equipment]

switch_to_activate_the_effect_of_broken_equ_on_proactive_plan = 1
DOCUMENT: Switch to activate the effect of brocken equipment on proactive maintenance plan [Dimensionless]

switch_to_activate_the_effect_of_staff_availability = 1
DOCUMENT: Switch to Activate Effect of Staff Availability of Preventive Maintenance [Dimensionless]

switch_to_activate_the_proactive_policy = 1
DOCUMENT: Switch to activate proactive policy (Dimensionless)

time_to_adjust_maintenance_staff = 1
DOCUMENT: Time to adjust maintenance staff [Years]

time_to_perceive_percentage_of_broken_equipment = 1
DOCUMENT: Time to perceive percentage of broken equipment repesent the time necessary for the management and decision makers to preceive and believe the percatage of broken equipment [Year]

time_to_take_equipment_for_proactive_maintenance = 2
DOCUMENT: Time to take equipment for proactive equipment [Years]

time_to_transfer_equipment_to_proactive_plan = 2.5
DOCUMENT: Time to transfer equipment to proactive plan represent average time to transfer equipment between proactive and reactive plans after an objective for the coverage of each plan is made (Year)

total_equipment = equipment_under_proactive_maintenance+equipment_under_proactive_maintenance_plan+ equipment_under_reactive_maintenance_plan+equipment_under_reactive_reapirs
DOCUMENT: Total quipment (Equipment)

total_operating_equipment = equipment_under_proactive_maintenance_plan+equipment_under_reactive_maintenance_plan
DOCUMENT: Total operating equipment [Equipment]

multiplier_from_broken_equipment_on_desired_maintenance_staff = GRAPH(perceived_percentage_of_broken_equipment_ratio)
(0.00, 0.125), (0.5, 0.425), (1.00, 1.00), (1.50, 1.40), (2.00, 1.73), (2.50, 1.95), (3.00, 2.13), (3.50, 2.25), (4.00, 2.35), (4.50, 2.43), (5.00, 2.48)
DOCUMENT: multiplier from broken equipment on desired maintenance staff [Fraction]

multiplier_from_broken_equipment_on_proactive_plan = GRAPH(perceived_percentage_of_broken_equipment_ratio)
(0.00, 0.275), (0.5, 0.5), (1.00, 1.00), (1.50, 1.43), (2.00, 1.83), (2.50, 2.18), (3.00, 2.45), (3.50, 2.68), (4.00, 2.83), (4.50, 2.93), (5.00, 3.00)
DOCUMENT: Multiplier from broken equipment on proactive maintenance plan (Dimensionless)

multiplier_from_staff_availability_on_proactive_plan = GRAPH(staff_availability_for_proactive__repair)
(0.00, 0.00), (0.5, 0.288), (1.00, 1.00), (1.50, 1.48), (2.00, 1.79), (2.50, 2.03), (3.00, 2.18), (3.50, 2.31), (4.00, 2.39), (4.50, 2.45), (5.00, 2.50)
DOCUMENT: Effect of Staff Availability on Preventive Maintenance Plan (Dimensionless)

multiplier_from_staff_availability_on_proactive__repair = GRAPH(staff_availability_for_proactive__repair)
(0.00, 0.00), (0.5, 0.5), (1.00, 1.00), (1.50, 1.38), (2.00, 1.75), (2.50, 2.03), (3.00, 2.25), (3.50, 2.38), (4.00, 2.48), (4.50, 2.48), (5.00, 2.48)
DOCUMENT: Multiplier from staff availability on proactive repair represents the effect of staff availability on proactive repair ofequipment that are taken out of operation for proactive maintenance (Dimensionless)

multiplier_from_staff_availability_on_reactive_repair = GRAPH(available_staff_for_reactive_repair/required_staff_for_reactive_repair)
(0.00, 0.00), (0.5, 0.5), (1.00, 1.00), (1.50, 1.40), (2.00, 1.80), (2.50, 2.13), (3.00, 2.40), (3.50, 2.63), (4.00, 2.80), (4.50, 2.93), (5.00, 3.00)
DOCUMENT: Multiplier from staff availability on reactive repair represents the effect of staff availability on the rate of reactive repair (Dimensionless)

multiplier_from_staff_availability_on_transfer_to_proactive_rep = GRAPH(staff_availability_for_proactive__repair)
(0.00, 0.00), (0.1, 0.02), (0.2, 0.065), (0.3, 0.15), (0.4, 0.33), (0.5, 0.645), (0.6, 0.795), (0.7, 0.89), (0.8,

0.94), (0.9, 0.98), (1, 1.00)

DOCUMENT Multiplier from staff availability on transfer of equipment to proactive repair represents the effect of maintenance staff availability on taking equipment for proactive maintenance When there is a shortage of staff time, proactive maintenance is postponed [Dimensionless]